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16. ABSTRACT

The paper describes recent developments of advanced combustion techniques for control of NOx and/or SOx for coal-, oil-, and gas-fired systems. Stationary combustion sources, particularly those fired with coal and oil, are major sources of NOx and SOx emissions. The commercially available combustion modification technology is relatively low cost; however, it gives a limited degree of control. Advanced combustion modification techniques are being developed which have the potential for greater NOx control effectiveness. The development of new or improved combustion systems is based on an understanding of the basic processes of NOx formation and control.

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ADVANCED COMBUSTION MODIFICATION

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ABSTRACT

Stationary combustion sources, particularly those fired with coal and oil, are major sources of NO_x and SO_x emissions. The commercially available combustion modification technology is relatively low cost; however, it gives a limited degree of control. Advanced combustion modification techniques are being developed which have the potential for greater NO_x control effectiveness. The development of new or improved combustion systems is based on an understanding of the basic processes of NO_x formation and control. This paper describes recent developments of advanced combustion techniques for control of NO_x and/or SO_x for coal, oil, and gas fired systems.

INTRODUCTION

Since the potential need for NO_x control technology in the U.S. was identified in the mid-1960's, a variety of options have been examined theoretically, experimentally, and in practical systems. For stationary combustion systems it has been generally accepted that the most cost effective technique is combustion modification. For commercial systems emphasis has been placed on external combustion modification techniques, such as flue gas recirculation and staged combustion, and on burner design. In general it has been found that flue gas recirculation is effective for gaseous fuels and light liquid fuels, whereas, staged combustion and burner design are effective for all fuels. While conventional combustion modifications are relatively inexpensive, their effectiveness is typically limited to 30 to 50 percent NO_x reduction. In an attempt to improve the effectiveness of combustion modification techniques, a number of advanced concepts are under development which have the potential for 80 to 90 percent reduction of emissions from uncontrolled levels. The purpose of this paper is to discuss the status of a number of advanced concepts developed under the U.S. EPA's NO_x Control Technology Program. In addition recent attempts to reduce SO_x emissions by sorbent addition with low NO_x firing systems will be described.

BACKGROUND

The basis for development of advanced combustion modification techniques is a basic understanding of the mechanisms of NO_x formation and control. The two sources of NO_x are: 1) formation of thermal NO_x by high temperature fixation of

molecular nitrogen from the combustion air; and 2) conversion of nitrogen chemically bound in the fuel to form fuel NO_x. Combustion modification techniques are divided into two broad classes: 1) temperature reduction to control the formation of thermal NO_x; and 2) reduction of oxygen availability in the combustion zone to minimize conversion of fuel nitrogen to NO_x. While both conventional and advanced combustion modification techniques are based on the same broad classes, the optimization of the advanced techniques depends on a further understanding of two additional phenomena: 1) the effects of fuel composition on nitrogen evolution and reaction; and 2) the effects of combustion process parameters, such as air/fuel mixing history and heat extraction, on pollutant formation. The advanced processes represent optimization of the combustion system to achieve minimum NO_x emissions as discussed below.

Fuel Effects

The effects of fuel composition on NO_x formation and control are dominant for high nitrogen liquid and solid fuels; for gaseous and low nitrogen liquids, fuel properties have only minor effects. As a result, the development of advanced combustion techniques draws heavily on data related to fuel effects. Since the effects for liquid fuels and coal are significantly different, each fuel is discussed separately.

Coal. Until recently no systematic evaluation of the effects of coal properties on NO_x formation and control has been available; however, Chen (Ref. 1) has investigated 50 coals from 5 continents under a variety of combustion conditions. The NO_x emissions from a 21 thermal kilowatt (70,000 Btu/hr) experimental system using a burner which rapidly mixes the coal and combustion air at fuel-lean conditions are shown in Figure 1. (Note: Only NO is shown since NO_2 is a small fraction of the NO_x.) The major points to note are:

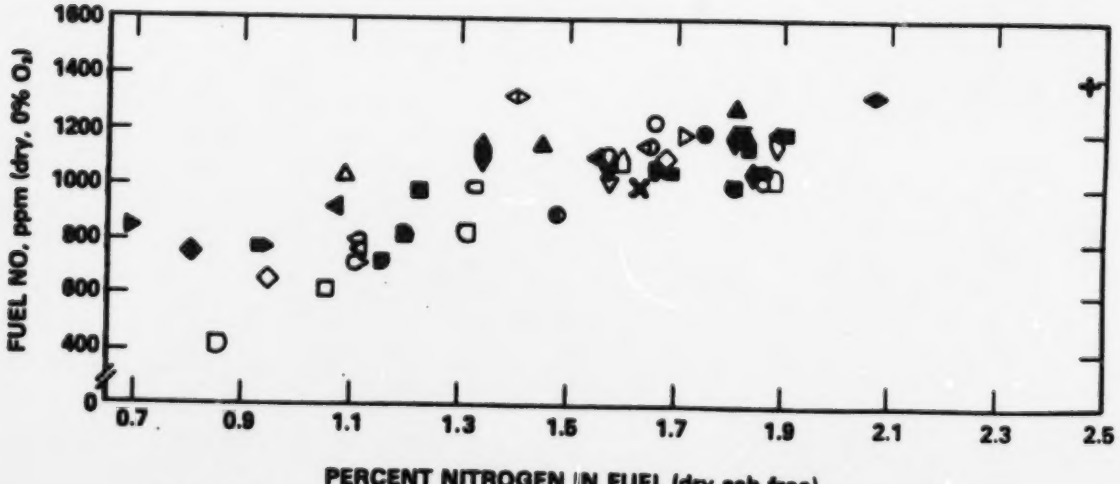


Figure 1. NO_x emissions from pulverized coal combustion under excess air conditions (Ref. 1)

1. NO_x emissions generally increase with increased fuel nitrogen; however,
2. For coals of similar rank and nitrogen content, the NO_x emissions can be significantly different.

He also found that the emissions correlated quite well with nitrogen evolution data from inert pyrolysis data.

The NO_x for staged combustion where the fuel-rich first stage was optimized for minimum NO_x emissions showed similar overall trends, with the absolute levels being reduced between 60 to 75 percent. He also showed that the minimum emissions were affected by the amount and type of volatile nitrogen species existing in the first stage and on the amount of nitrogen left in the char.

These results show the potential for significant effects of coal properties on the NO_x levels achievable for advanced systems. They also indicate the need for systems which drive the bulk of the nitrogen into reduced volatile nitrogen species in the first stage.

Liquid Fuels. Most petroleum derived liquid fuels have some fuel nitrogen content; however, the nitrogen tends to concentrate in the residual fuel oils, which may contain more than 0.8 percent by weight. Alternative liquid fuel derived from shale- and coal-derived crudes may have over 2 percent nitrogen by weight, and the nitrogen is more uniformly distributed through the product spectrum. The emission characteristics of a variety of petroleum-,shale-, and coal-derived liquids have been reported by England (Ref. 2) for a small experimental furnace. The results shown in Figure 2 show that the NO_x emissions correlate well with total fuel nitrogen content. He has also shown that emissions under staged conditions correlate with overall fuel nitrogen content. The results suggest that nitrogen containing liquid fuels do not exhibit the wide differences in fuel nitrogen evolution seen in coal.

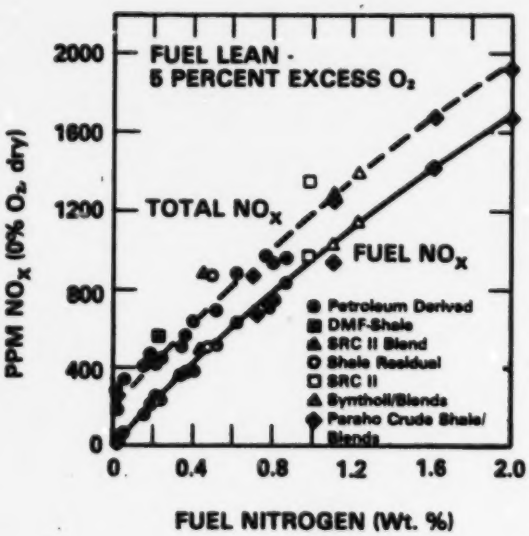


Figure 2. The effect of fuel nitrogen content on total and fuel NO_x (Ref. 2)

Combustion Parameters

The key to the success of advanced concepts is the control of combustion parameters such as air/fuel mixing, fuel-rich residence time, and/or rate and

location of heat extraction. The small scale studies discussed above and larger scale experiments have provided valuable insights on the approaches that can be taken to achieve optimum combustion conditions for minimum NO_x emissions. Three techniques that form the basis for the advanced concepts to be discussed are burner design, prechamber burner, and novel concepts.

Burner design. The advanced concepts that are most readily adaptable to existing furnace design are based on controlling air/fuel mixing aerodynamically by changes in burner design. This approach involves fuel and air introduction schemes which create a fuel-rich core in the flame for fuel NO_x control and a surrounding air-rich zone for carbon burnout. The distributed mixing coal burner is an example of this approach.

Prechamber burner. Considerably better control of combustion parameters can be achieved by providing a physical separation of the fuel-rich zone and the subsequent burnout zone. In this approach the thermal environment can also be better controlled. A prechamber burner provides these conditions, and minimum emissions can be achieved as described for the heavy oil burner.

Novel concepts. For certain applications it is possible to abandon the diffusion flame entirely and use a new approach to fuel combustion. This is particularly true for gaseous fuels where mixing problems are minimal and control of thermal environment is a key parameter. Catalytic combustion is an approach described below.

RECENT DEVELOPMENTS

The EPA has an ongoing program for the development of advanced combustion modification techniques for fossil and alternative fuels. This section will describe the status of selected advanced concepts including: 1) distributed mixing systems for pulverized coal fired boilers; 2) sorbent injection through multistage burners for SO_x control; 3) fuel and air distribution techniques for spreader stoker boilers; 4) prechamber furnaces for liquid fuels; and 5) catalytic combustors for gaseous fuels.

Distributed Mixing Systems

The distributed mixing system involves changes in the air and fuel introduction hardware of pulverized coal fired boilers to achieve aerodynamically staged combustion. The technique has been developed for both wall-fired and tangentially fired boilers and is being evaluated at field installations.

Wall-fired boilers. The system for wall-fired boilers is called the distributed mixing burner (DMB). The DMB concept was developed from EPA sponsored work at the International Flame Research Foundation and has subsequently been

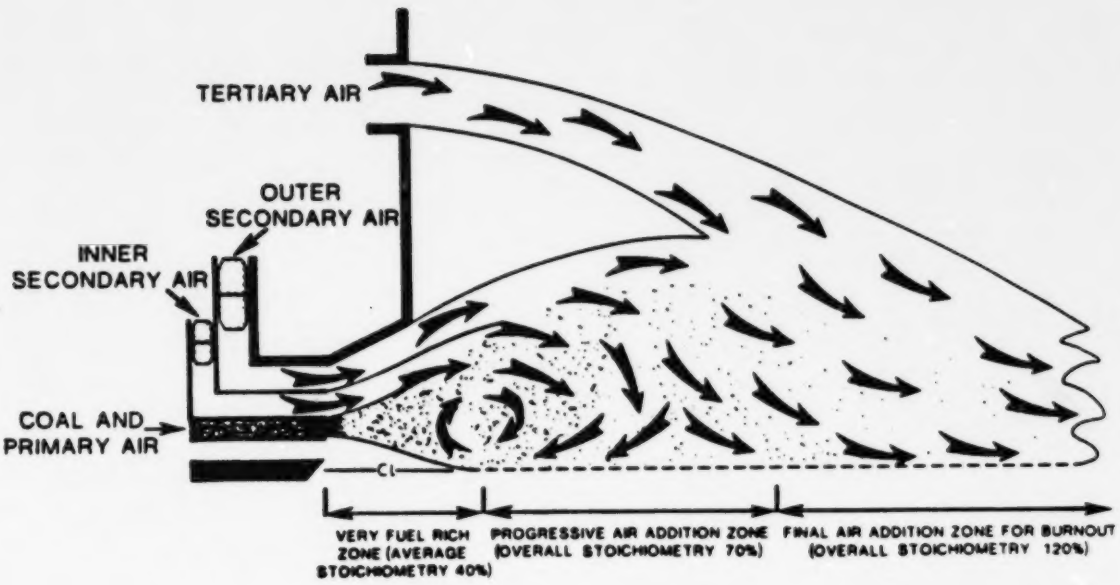

TERTIARY AIR
OUTER SECONDARY AIR
INNER SECONDARY AIR
COAL AND PRIMARY AIR
VERY FUEL RICH ZONE (AVERAGE STOICHIOMETRY 40%)
PROGRESSIVE AIR ADDITION ZONE (OVERALL STOICHIOMETRY 70%)
FINAL AIR ADDITION ZONE FOR BURNOUT (OVERALL STOICHIOMETRY 120%)

Figure 3. Schematic of distributed mixing burner concept

scaled up to full scale for practical boilers (i.e., 30 thermal kilowatt or over 100 x 10^6 Btu/hr). The basis of the burner is shown in Figure 3. The coal is introduced through a central fuel injector with about 25 percent of the combustion air (called primary air). Secondary air is introduced through concentric passages of the burner throat in an amount to bring the total air through the burner to 60 to 80 percent of the air theoretically required for complete combustion of the coal. The initial coal devolatilization and reaction takes place in this fuel-rich zone, thereby minimizing fuel nitrogen conversion to NO_x. Finally the balance of the combustion air, totaling 120 percent theoretical air, is introduced through tertiary ports surrounding the burner. This gradually mixes with the rich primary and provides for complete carbon burnout. An artist's conception of the burner installed in a boiler is shown in Figure 4. Large pilot scale testing in an experimental system has shown the potential for NO_x emissions below 86 nanogram per joule (0.2 lb/10^6 Btu or about 150 ppm).

The DMB concept has been incorporated into a prototype burner (24 thermal megawatt or 80 x 10^6 Btu/hr input) and tested in the experimental furnace. The emission performance is shown in Figure 5 (Ref. 3) for two fuels. For one coal, an Indiana bituminous which is used at the field installation, the effect of secondary air parameters is also shown. At the optimum condition, both coals give NO_x emissions below 129 nanogram per joule (0.3 lb/10^6 Btu). In all cases CO emissions were below 100 ppm.

The prototype burner design has been installed in a four burner, 20 electrical

megawatt boiler at the Western Illinois Power Cooperative's Pearl station. The burner has been operating in a nominally staged mode for 6 months, and full staged operation will commence in the summer of 1982. Preliminary estimates indicate that NO_x emissions below 86 nanogram per joule can be achieved.

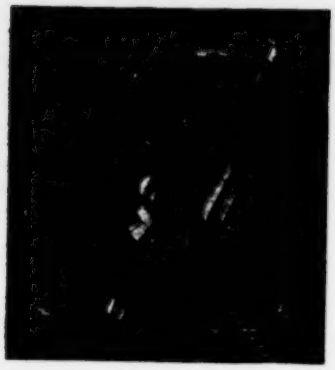


Figure 4. Artist's conception of DMB installed on a boiler

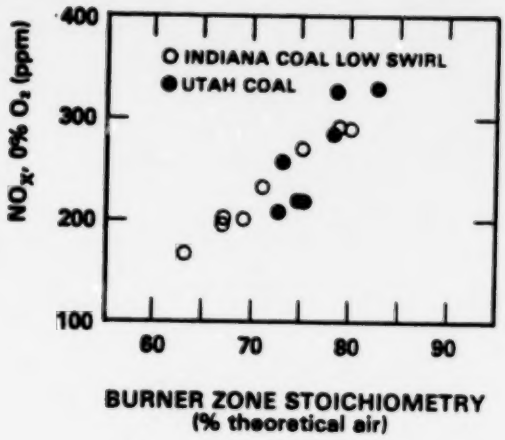


Figure 5. Prototype burner performance (Ref. 3)

Tangentially fired boilers. Since tangentially fired boilers are furnace-stabilized systems rather than burner-stabilized systems, a different embodiment of the distributed mixing approach is required. A schematic of the rich fireball system is shown in Figure 6. The coal and primary air are fired on the tangent of an imaginary circle as in conventional practice; however, the balance of the combustion air is diverted closer to the furnace wall. This produces a fuel-rich zone in the center of the fireball for NO_x reduction, and an air-rich zone for carbon burnout and protection of the furnace wall from corrosion. This system has been tested at small pilot scale (Ref. 4) and showed the potential for NO_x emissions below 129 nanogram per joule.

The rich fireball has been installed on a 400 electrical megawatt boiler at the Hunter station of Utah Power and Light Company. In recent shakedown tests NO_x emissions approaching 129 nanogram per joule have been achieved. Once the operating conditions for continuous operation are selected, the system performance will be evaluated over an 18 month period.

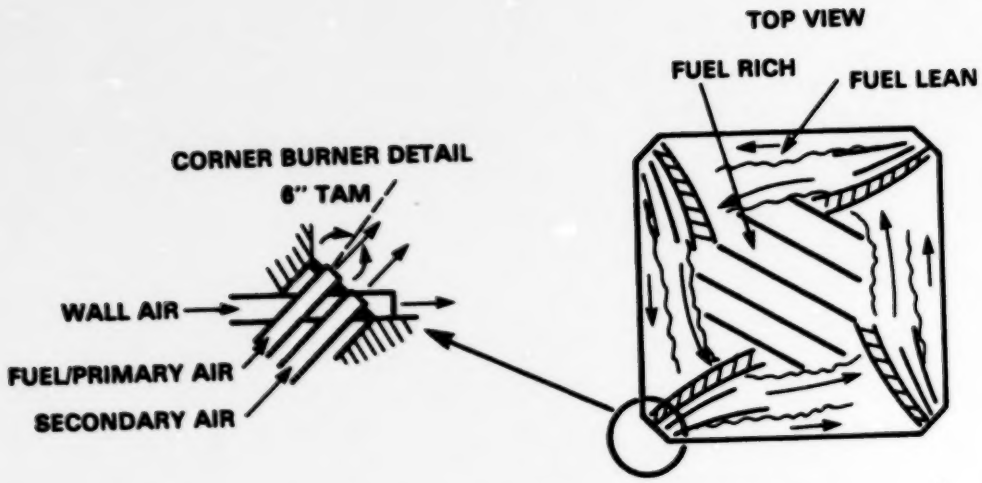


Figure 6. Schematic of rich fireball for tangentially fired boilers (Ref. 4)

Limestone Injection Through Multistage Burners (LIMB)

An analysis of theoretical data suggested that the DMB concept might create conditions suitable for sulfur capture by sorbent materials. Zallen (Ref. 5) ran a preliminary series of experiments with a 3 thermal megawatt (10×10^6 Btu/hr) DMB in an experimental facility and reported high capture efficiencies (i.e., up to 70 percent SO_x reduction with a calcium to sulfur ratio of 2). Various reasons for the high capture were postulated, including: 1) reduced peak temperatures, 2) existence of a fuel-rich zone where reduced sulfur species are captured directly, 3) intimate sorbent sulfur contact, and 4) in-situ activation of the sorbent. As a result of these findings the EPA initiated a development program to confirm the potential of the technique to establish the critical parameters for sulfur capture and to define approaches to practical application. To date the effort has been concentrated on bench scale experiments and prototype burner testing.

Bench scale results. The bench scale studies have been carried out by Case (Ref. 6) in a 300 thermal kilowatt (1×10^6 Btu/hr) facility called the Boiler Simulator Furnace (BSF). The BSF is designed to provide control of temperature and/or residence time of combustion products from the burner zone to the stack over the range typical of practical boilers. The furnace variables include, burner zone stoichiometry, sorbent injection, heat extraction, and fuel type. Figure 7 compares the range of sulfur capture in the BSF with past data from experimental systems and for furnace injection of sorbent for a practical boiler. The broad crosshatched area, which shows the BSF data, indicates that sulfur captures can range from 10 to 70 percent at a calcium to sulfur ratio of 2, depending on operating conditions. For overall fuel-lean combustion zone operation, the primary variable is temperature, with high captures achieved with

high heat extraction from the radiant zone. For staged operation the capture appears to be less sensitive to temperature. Further work is in progress to fully identify the controlling parameters.

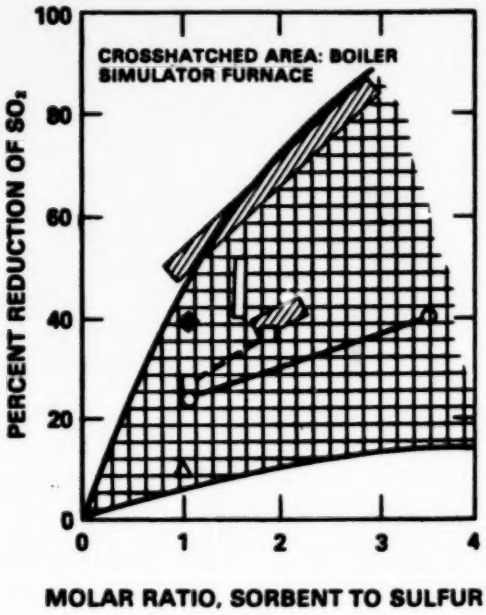


Figure 7. Range of sulfur capture achievable in BSF compared to data for other systems

Prototype testing. The DMB prototype burner discussed earlier has been evaluated for sulfur capture by sorbent injection in a limited series of tests in two large experimental facilities (Ref. 6). One facility, the large watertube simulator (LWS), has a thermal environment similar to industrial coal fired boilers. The other, the medium tunnel (MT), has a hotter burner zone environment. The sorbent was either pulverized with the coal or injected with the tertiary air when the burner was operating at low NO_x conditions. Data for prototype testing is shown in Figure 8a for the LWS for two coals. For the high sulfur Indiana coal, the sulfur capture was essentially the same regardless of sorbent injection location and was about 50 percent at a calcium to sulfur ratio of 2. For the low sulfur Utah coal the sulfur capture was lower than for the Indiana coal, and injection with the coal gave better results. Data from the MT in Figure 8b shows similar trends with fuels; however, it appears that in the hotter environment, sorbent injection with the coal provides better capture than injection with the air.

Practical application. Application of the technology will be dependent on the sulfur capture potential achievable in the combustion environment of a range of practical boilers. In addition the impacts of the sorbent addition on boiler operation (e.g., slagging and fouling) and on post treatment device efficiency (e.g., particulate control equipment) must be evaluated. An engineering design study is in progress to address these and other questions.

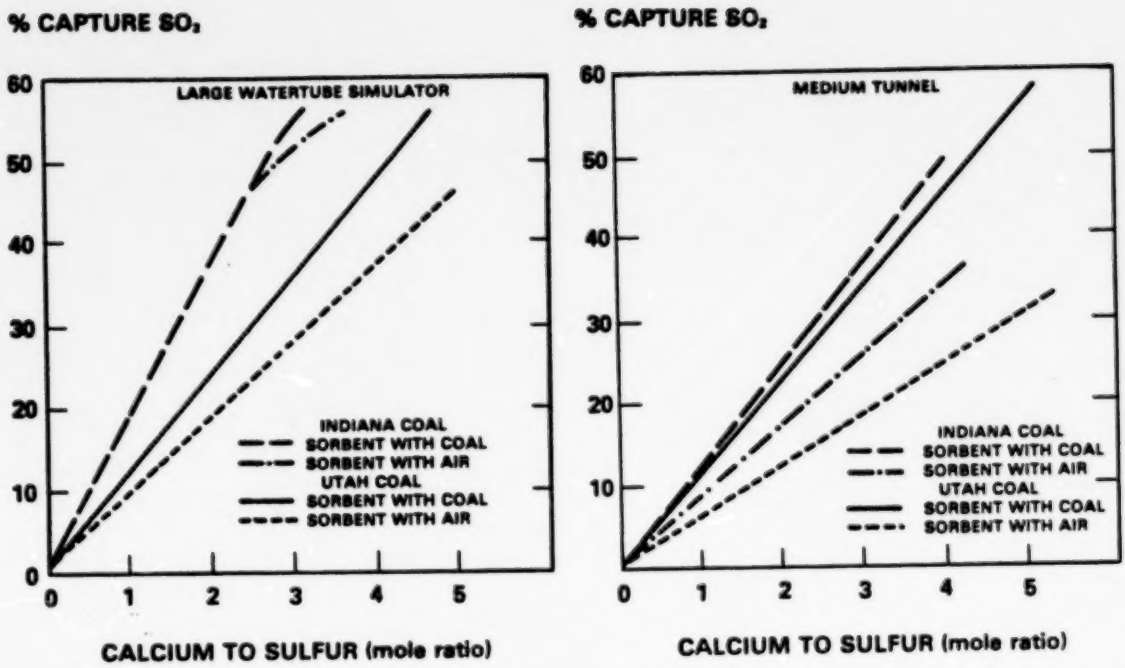


Figure 8. Sulfur capture with prototype burner in: a) the large watertube simulator and b) the medium tunnel

Stoker Coal Fired Concepts

In the past only limited attention has been given to NO_x control for stoker systems although this type of boiler makes a significant contribution to NO_x emissions. Field evaluation of operating changes shows that these changes (e.g., air distribution) are typically much less effective for NO_x control for stokers than for other coal fired boilers. Recent R&D has investigated the combustion processes occurring in stoker systems. In all stoker systems there is a bed of burning coal supported by a grate of some kind, and the phenomenon of bed burning has a significant effect on pollutant emissions. For spreader stokers the coal is deposited on the grate by being "thrown" from a distance over the bed. This results in entrainment of coal fines by hot gases rising from the bed and a portion of the coal fines being burned under conditions similar to those of pulverized coal firing. Both bed burning of the raw coal and suspension-phase combustion of the fines have been investigated in simple experimental systems. Major conclusions are:

1. Even for spreader stokers, between 80 and 90 percent of the coal is burned on the bed. The conversion of fuel nitrogen to NO_x is about 15 percent for fuel-lean beds. The conversion may be reduced to less than 5 percent by operation of the bed in a fuel-rich mode (Ref. 7).
2. Dependent on the amount of fines in the raw coal, between 8 and 20 percent

of the coal will burn in the suspension phase of a spreader stoker. Under fuel-lean conditions about 40 percent of the fuel nitrogen will be converted to NO_x. This conversion can be reduced by fuel-rich operation of the suspension zone. It also appears that incomplete combustion of the coal fines can contribute significantly to unburned carbon in the fly ash (Ref. 7).

3. A series of experiments was performed with coal pellets which contained limestone sufficient to give a calcium to sulfur ratio of 3.5. For fuel-lean operation the SO_2 emissions are reduced from 3655 to 1290 nanogram per joule (8.5 to 3.0 lb $SO_2/10^6$ Btu). Under staged combustion conditions the SO_x is further reduced to about 645 nanogram per joule (1.5 lb $SO_2/10^6$ Btu). This shows the potential importance of fuel-rich conditions on sulfur capture. This effect needs to be explored for lower calcium to sulfur ratios to determine if better enhancement is possible (Ref. 8).

As a result of these investigations, several control concepts have been postulated and tested (Ref. 7) in a model spreader stoker as shown in Figure 9. In this system coal is fed to the spreader which distributes the coal onto a fixed grate. Combustion air is supplied from under the grate and through overfire air ports to simulate arrangement in practical systems. The results obtained include:

1. For staged combustion the amount of air introduced under the bed is reduced and the amount of overfire air is increased to maintain a constant overall level of 1.4 times the amount required for complete combustion (SR = 1.4). As the bed stoichiometric ratio (S.R.) is reduced, NO_x levels decrease and a maximum reduction is achieved at an S.R. of 0.8. The level of reduction depends on the height of overfire air injection, with the larger separation giving lower NO_x as shown in Figure 10. At the optimum conditions a 65 percent reduction was achieved.

2. Since the fines combustion accounts for a significant portion of the NO_x from spreader stokers, an experiment was run where the fines (i.e., particles smaller than 0.279 cm or 0.111 in.) were removed from the coal feed prior to combustion. This relatively simple change gave a 20 to 25 percent reduction of NO_x. Staged combustion further reduced the emissions; however, overfire air height had relatively little effect, indicating the significance of suspension zone reactions on NO_x formation (Ref. 9).

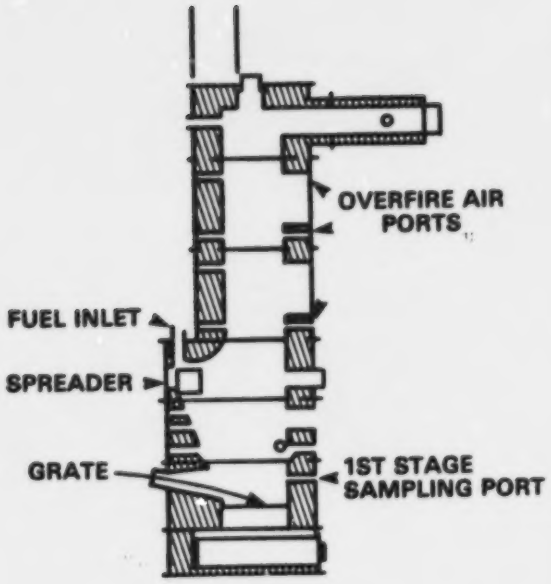


Figure 9. Schematic of model spreader stoker (Ref. 7)

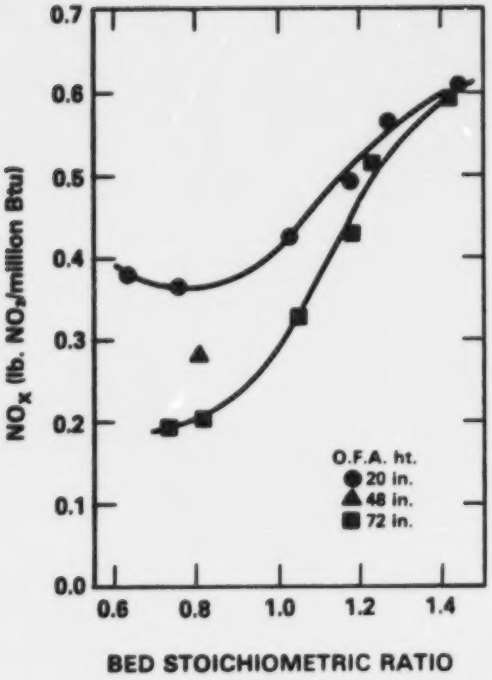


Figure 10. Effect of bed stoichiometry and overfire air height on NO_x from model spreader stoker*

Liquid Fuel Burner

The small scale fuel screening of petroleum and alternative liquid fuels discussed earlier also led to a concept for highly effective control of fuel NO_x. Staged combustion experiments showed that, if the heat loss from the fuel-rich zone was very low, NO_x emissions could be reduced over 90 percent for a 2 percent nitrogen shale-derived crude. It further showed that under optimum staged conditions NO_x levels were relatively independent of the nitrogen content of the oil. Based on these results a prechamber liquid fuel burner concept was derived for application to package boilers and process heaters (Ref. 10). A 600 thermal kilowatt (2×10^6 Btu/hr) prototype burner, as shown in Figure 11, was constructed and tested in an experimental facility similar to a scotch marine firetube boiler. The performance of the prototype burner with a 0.98 percent nitrogen coal-derived liquid fuel is shown in Figure 12. At a burner zone SR of 0.7 (70 percent of the air required for complete fuel combustion) NO_x emissions were reduced to 55 ppm

*NOTE. It is EPA policy to use metric units; however, for figures derived from references using English units the units are not converted to metric. For metric equivalents see table at the end of the paper.

with a very low smoke number. This represents a reduction of over 90 percent from the base level of 850 ppm. The performance of the prototype for a range of high nitrogen fuels was evaluated, and the NO_x emissions for the prototype burner were below 80 ppm for all liquid fuels. Also the prototype produced lower NO_x emissions than the screening furnace, probably due to surface to volume effects which reduce heat loss at the larger scale. The prototype burner provided the following design guidance: 1) the first stage should be run as hot as possible, 2) the fuel-rich residence time should be greater than 200 ms, and 3) second-stage heat removal and air injection are not primary variables.

Based on these results a 3.6 thermal megawatt (12×10^6 Btu/hr) prototype has been tested and produced similar NO_x emissions performance. The burner will subsequently be scaled up to 18 thermal megawatt (60×10^6 Btu/hr) and tested on an oil field steam generator.

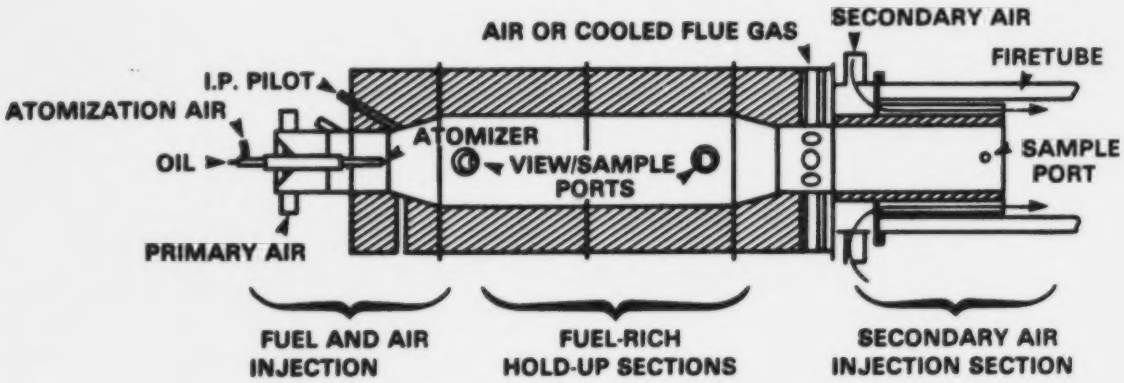


Figure 11. Schematic of heavy liquid fuel burner (Ref. 10)

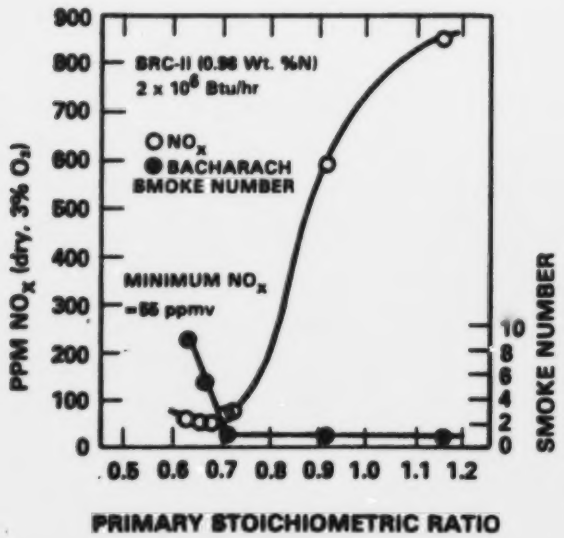


Figure 12. NO_x emissions for optimized heavy liquid fuel burner

Catalytic Combustion

The use of catalysts as cleanup devices has been known for some time; however catalysts have been explored as a primary combustion device only in the last few years. In this application the catalyst is used to promote the combustion of the fuel and serves as a major energy release device in a combustion system. The catalyst shortens reaction times and can result in very low levels of pollutants (NO_x, CO, and unburned hydrocarbon) if properly applied. The main problem is interfacing the catalyst with the practical combustion system. A number of applications have been studied (Ref. 11). To date the most success has been achieved with gaseous and light liquid fuels, since the catalyst typically requires a homogeneous air/fuel mixture, with emphasis on control of thermal NO_x.

One of the most advanced concepts is the fiber burner for application to gas fired package boilers and process furnaces. A high temperature ceramic fiber is deposited over an external support screen. Premixed air and fuel are fed to the inside of the fiber burner, pass through the fiber cylinder, and are ignited and burn on the outer surface. The surface is placed in close proximity to a heat transfer surface so that about 50 percent of the energy release is transferred from the burner surface by radiation. This serves two purposes: 1) it maintains the temperature of the ceramic fiber well within its operating limit, and 2) it reduces the formation of thermal NO_x. A schematic of a fiber furnace for a scotch marine firetube boiler is shown in Figure 13 (Ref. 11). A prototype system has been constructed and tested in a 300 thermal kilowatt (10^6 Btu/hr) firetube boiler. The NO_x emissions are shown in Figure 14a and boiler efficiency is shown in Figure 14b. At 100 percent load firing natural gas, NO_x emissions are 10 ppm as compared to 70 ppm from the conventional burner. At this condition CO and unburned hydrocarbon (UHC) emissions are less than or equal to those of the conventional burner. It also appears that a portion of the NO_x, CO, and UHC emissions are attributable to thermal combustion of the fuel/air mixture short-circuiting through fiber pad imperfections. The boiler efficiency is increased by

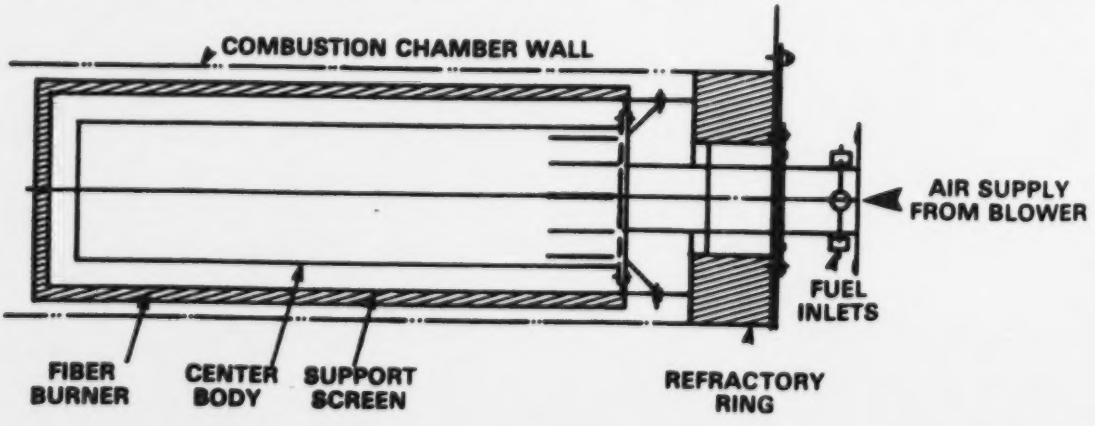
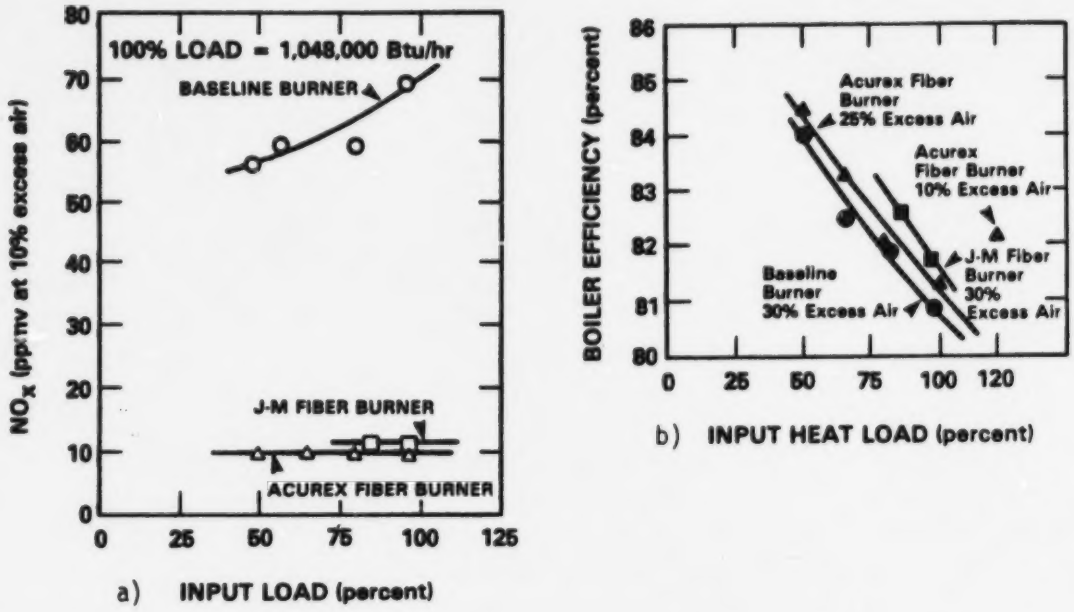


Figure 13. Schematic of fiber burner assembly (Ref. 11)

about 1 percent at 100 percent load and normal excess air loads. Since the fiber burner can operate at lower excess air and higher load without excessive CO and UHC emissions, the system efficiency can be increased an additional 0.5 percent at 120 percent of rated steam production.


100% LOAD = 1,048,000 Btu/hr
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J-M FIBER BURNER
ACUREX FIBER BURNER
NO_x (ppmv at 10% excess air)
a) INPUT LOAD (percent)
BOILER EFFICIENCY (percent)
Acurex Fiber Burner 25% Excess Air
Acurex Fiber Burner 10% Excess Air
J-M Fiber Burner 30% Excess Air
Baseline Burner 30% Excess Air
b) INPUT HEAT LOAD (percent)

Figure 14. Performance of fiber burner in a firetube boiler: a) NO_x emissions; and b) efficiency

SUMMARY

The EPA program for advanced combustion modification technique development has provided an understanding of the effects of combustion conditions and fuel characteristics on NO_x formation and control. The main focus of the program has been controlling fuel NO_x emissions from nitrogen containing solid and liquid fuels. Fundamental and small pilot scale work has provided insight into the role of fuel nitrogen volatility on NO_x formation from coal, heavy oil, and synthetic liquid fuels.

The advanced combustion modification development program has placed the greatest emphasis on staged burner development for control of fuel NO_x from high nitrogen solid and liquid fuels. In addition, novel combustion techniques for clean fuels have been investigated. A summary of the developments described in this paper follow.

1. Prototype testing of distributed mixing systems for pulverized coal firing has shown the potential for controlling NO_x emissions to the level of 86 to 129 nanogram per joule (0.2 to 0.3 $lb/10^6$ Btu). Field evaluation results from retrofit of these systems indicate that emissions will fall at the upper end of that range. New systems specifically designed for these firing systems appear to have the potential to achieve the lower end of the range.

2. Several novel systems for stoker coal have been developed based on fuel rich operation of the bed region and control of conversion of fuel nitrogen in the small coal particles. Further development is required; however, it appears that NO_x reduction over 65 percent is possible.

3. A preburner system for high-nitrogen liquid fuels has been scaled up from 21 thermal kilowatts to 3.6 thermal megawatts (70,000 to 12 x 10^6 Btu/hr). NO_x emissions from a given fuel generally decrease with increased scale. Absolute NO_x levels are below 100 ppm with very low carbonaceous particulate emissions.

4. The fiber burner approach to catalytic combustion appears to be feasible for package boilers and process furnaces. Evaluation in a small firetube boiler indicates a potential for NO_x reductions up to 85 percent with low levels of CO and unburned hydrocarbons. Both steam generation capacity and system efficiency are increased.

5. The use of sorbents in conjunction with low NO_x combustion techniques for pulverized- and stoker-coal-fired systems appears to have potential for substantial SO_x control. Based on large prototype burner testing and bench scale experiments, LIMB has the potential to achieve 50 percent SO_x reduction on retrofit systems and a higher degree of control for new systems.

6. These and other advanced combustion modification techniques under development have the potential for highly effective NO_x control at moderate cost. The coupling of low NO_x and SO_x is a particularly attractive technical option, assuming it can be accomplished at reasonable cost.

REFERENCES

1. S.L. Chen, M.P. Heap, D.W. Pershing, and G.B. Martin. The Fate of Volatile and Char Nitrogen During Combustion of U.S. and World Coals. To be presented at the 19th Symposium (International) on Combustion, Haifa, Israel, August 1982.
2. G.C. England, M.P. Heap, D.W. Pershing, J.H. Tomlinson, and T.L. Corley. Low NO_x Combustors for High Nitrogen Liquid Fuels. Proceedings of the Joint Symposium on Stationary Combustion NO_x Control, Volume IV. EPA-600/9-81-028d, NTIS PB 81-236-143, July 1981.
3. A. Abele, J. Reese, B. Folsom, and J. Vatsky. Development of a Low NO_x Distributed Mixing Burner for Pulverized Coal Fired Industrial Boilers APCA Paper No. 82-60.1. To be presented at 75th APCA Annual Meeting, New Orleans, LA, June 1982.
4. J.T. Kelly, R.A.Brown, J.B. Wightman, R.L. Pam, and E.K. Chu. Pilot Scale Evaluation of a Low NO_x Tangential Firing Method. Proceedings of the Joint Symposium on Stationary Combustion NO_x Control, Volume I. EPA-600/9-81-028a, NTIS PB 81-236-119, July 1981.
5. D.M. Zallen, R. Gershman, M.P. Heap, and W.H. Nurick. The Generalization of Low Emission Coal Burner Technology. Proceedings of the Third Stationary Source Combustion Symposium, Volume II. EPA-600/7-79-050b, NTIS PB 292-540, February 1979.
6. P.L. Case, M.P. Heap, R. Payne, and D.W. Pershing. The Use of Dry Sorbents to Reduce Sulfur Oxide Emissions from Pulverized Coal Flames Under Low NO_x Conditions. Presented at the Central States Section Meeting of the Combustion Institute, Columbus, OH, March 1982.
7. G.P. Starley, P.M. Slaughter, J.M. Munro, D.W. Pershing, and G.B. Martin. Formation and Control of NO_x Emissions from Coal-Fired Spreader-Stoker

Boilers. To be presented at the 19th Symposium (International) on Combustion, Haifa, Israel, August 1982.
8. S.C. Manis, D.W. Pershing, and G.P. Starley. Parameters Influencing Formation of SO_x Emissions in Stoker-Fired Fixed-Bed Coal Combustion. Presented at the Central States Section Meeting of the Combustion Institute, Columbus, OH, March 1982.
9. J.W. Munro and D.W. Pershing, Formation and Control of NO_x Emissions from Coal-Fired Spreader Stoker Systems. Paper No. 82-60.3. To be presented at the Air Pollution Control Association Annual Meeting, New Orleans, LA, June 1982.
10. G.C. England, M.P. Heap, and D.W. Pershing. Development of a Low NO_x Burner Suitable for High Nitrogen Liquid Fuels. Draft Final Report, EPA Contract 68-02-3125.
11. E. B. Merrick, W. V. Krill, J.P. Kesselring, and M.A. Friedman. Development of a Low NO_x Combustor for Gas-Fired Firetube Boilers. Presented at the Fifth Workshop on Catalytic Combustion, San Antonio, TX, September 1981.

Metric Equivalents

0.1 lb/10^6 Btu = 43 nanogram/Joule
1 inch = 2.54 cm
10^6 Btu = 300 thermal megawatts